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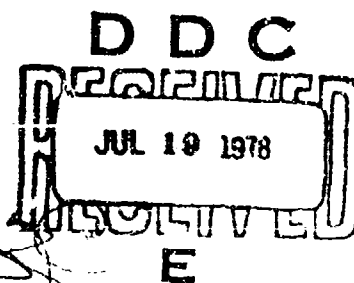
## APPLICATIONS OF POLARIZATION-DIVERSITY RADAR AND LIDAR IN METEOROLOGY

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demonstrated capabilities and identification of limiting factors associated with equipment design or meteorological parameters. Measurement capabilities and operational benefits of a coherent polarization-diversity radar are discussed. Prospects for the use of lidar in distinguishing high-altitude aerosol layers from clouds are described.

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## I. INTRODUCTION

Over the past several decades techniques involving polarization-diversity have received intermittent emphasis in radar meteorological research. In a preceding report <sup>(1)</sup> the major theoretical and experimental programs were identified and reviewed. Most of these programs were developed in response to particular operational needs, such as the detection of hail in severe storms, improved penetration of precipitation by electromagnetic signals, and minimizing depolarization of signals in precipitation. In recent years other suggested operational goals such as improved rainfall measurement and higher unambiguous velocity measurement have involved application of polarization diversity techniques.

It is the purpose of the present report to provide an evaluation of the applications which have been suggested or implemented. Foremost of these is the determination of various parameters of the scattering medium: thermodynamic phase, size, shape, and orientation. Such determinations have obvious relevance to such problems as hail detection and weather modification. Backscatter measurements of these parameters can also provide information about precipitation as a propagation medium. Other specific applications include the use of differential reflectivity at orthogonal linear polarizations to measure rainfall rate and the use of polarization agility to achieve higher unambiguous velocity measurements in severe storms. The former has been implemented experimentally and preliminary results are available; the latter has not been implemented due

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(1) Metcalf, J. I., Brookshire, S. P., and Morton, T. P., 1978: Polarization-Diversity Radar and Lidar Technology in Meteorological Research: A Review of Theory and Measurements. Sci. Rpt. 1, Contract F19628-77-C-0066, Engr. Expt. Stn., Ga. Tech.; AFGL-TR-78-0030, Air Force Geophysics Lab.

to the complexity of the required equipment relative to the expected benefits. Determination of the propagation parameters of the atmosphere continues to be of interest as higher microwave frequencies come into use for communications and military systems and as more stringent performance characteristics are sought for systems operating at lower microwave frequencies. Both forward propagation and backscatter experiments have been used for this purpose. The polarization properties of backscatter from meteorological and non-meteorological targets have been used or suggested for selectively discriminating against one or the other of these classes of targets. The current status of research in each of these applications is described in the following sections and the prospects for future developments are discussed.

We also address the prospects for beneficial application of two developing areas of polarization-diversity technology: the coherent polarization-diversity radar and the polarization-diversity lidar. The former represents a combination of techniques, each of which has proven capabilities but which have not been used in combination except in limited ways. The latter is an area which has seen rapid equipment development in the past few years but which has some serious limitations in its present applicability to atmospheric measurements. We discuss the limitations on each of these areas due to equipment capabilities and to the propagation and scattering characteristics of the atmosphere.

Our notation follows that of the preceding report. With reference to a dual-channel receiver the depolarization ratio (circular or linear) is the ratio of received power in the orthogonal channel to that in the main channel.



If circular polarization is transmitted the main channel return is of opposite polarization to the transmitted signal; if linear polarization is transmitted the main channel is parallel to the transmitted polarization. The depolarization ratio is nearly always less than unity for meteorological backscatter, and is expressed in decibels for radar and as a ratio for lidar in accordance with present usage in the literature. The cancellation ratio is the ratio of the orthogonal channel power when circular polarization is transmitted to the main channel power when linear polarization is transmitted, and describes the improvement in clutter "cancellation" in a single-channel radar achieved by the use of circular polarization rather than linear. In the case of randomly oriented scatterers the cancellation ratio is equal to the circular depolarization ratio. If the scatterers are preferentially oriented, the cancellation ratio may be several dB greater or less than the circular depolarization ratio, depending on the ellipticity of the scatterers and the orientation of the plane polarization relative to the symmetry axes of the scattering medium. In measurements of propagation parameters the term cross-polarization is used to describe the received signal component having a polarization state orthogonal to that of the transmitted signal.

## II. HYDROMETEOR PARAMETERS

### A. THERMODYNAMIC PHASE

The linear depolarization ratio (LDR) of radar and lidar returns from clouds and precipitation may be used to indicate the target's thermodynamic phase. Spherical hydrometeors (liquid cloud particles and small rain drops) always yield radar LDR's less than -18 dB and crystalline hydrometeors always yield LDR's greater than -9 dB. <sup>(2,3)</sup> LDR's between -18 and -9 dB indicate crystalline or mixed-phase clouds with values closer to -18 dB indicating predominately liquid and values closer to -9 indicating predominately solid hydrometeors. The LDR's associated with various hydrometeors are shown in Table 1, which is extracted from Minervin and Shupyatskiy. <sup>(2)</sup>

Some earlier American and British effort <sup>(4,5,6)</sup> was also directed toward polarization diversity thermodynamic phase discrimination, largely by use of differential reflectivity and cancellation ratio (as defined in the Introduction). Newell et al <sup>(6)</sup> measured reflectivity, cancellation ratio and differential reflectivity between vertical and horizontal transmissions

- 
- (2) Minervin, V. Ye., and Shupyatskiy, A. B., 1966: Investigation of the Phase State of Clouds with the Aid of Radar. Izv. Acad. Sci., USSR, Atmos. and Oceanic Phys., 2, 562-568.
  - (3) Minervin, V. Ye., and Shupyatskiy, A. B., 1968: Investigations of Cb Phase Structure by Means of Radar Signal Polarization Characteristics. Proc. 13th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, 34-35.
  - (4) Browne, I. C., and Robinson, N. P., 1952: Cross-Polarization of the Radar Melting Band. Nature, 170, 1078-1079.
  - (5) Austin, P. M., and Bemis, A. C., 1950: A Quantitative Study of The "Bright Band" in Radar Precipitation Echoes. J. Meteor., 7, 145.
  - (6) Newell, R. E., Geotis, S. G., and Fleisher, A., 1957: The Shape of Rain and Snow at Microwavelengths. Res. Rept. 28, Dept. of Meteorology, Mass. Inst. of Technology, Cambridge.

TABLE 1

## LINEAR DEPOLARIZATION RATIOS OF VARIOUS HYDROMETEORS AT 3.2 cm

Object of Study	Shape of Crystals	Size, mm	Shape of Ellipsoid	Ratio Between Axes	Preferential Orientation of the Axis of Rotation	Depolarization ratio, dB	
						from	to
Snow	plates	1-4	flattened	1:8 - 1:5	vertical	-8.6	-5.2
	stars	0.5-7	flattened	1:30 - 1:200	vertical	-5.8	-4.0
	columns	0.5-5	elongated	1:1 - 8:2	horizontal	-∞	-13
	short columns	up to 1	flattened	1:1 - 1:2	vertical	-∞	-15
	needles	up to 5	elongated	5:1 - 25:1	horizontal	-14	-6
	fuzz	up to 7	flattened	1:3 - 1:100	vertical	-12	-5
	granular snow	0.2-10	sphere	1:1		-∞	
	columns	0.02-1	elongated	1:1 - 8:1	horizontal	-∞	-12
	plates	up to 1	flattened	1:1 - 1:50	vertical	-8.6	-5.2
	needles	0.05-0.25	elongated	3:1 - 60:1	horizontal	-15	-5
Cloud Crystals	aggregates of columns	up to 1	flattened	up to 1:10	vertical	-∞	-8
Raindrops		2.5	sphere	1:1	vertical		
		4	oblate	1:1.3	vertical		
		4.8	oblate	1:1.5	vertical	-∞	-14
		5.2	oblate	1:1.6	vertical		

to determine the distortions of particles in the melting layer. Although they detected significant hydrometeor distortion through the melting layer, they were unable to determine a preferred orientation. They also reported large cancellation ratios associated with hail in one observation and with frozen rain drops in another. One other hail-producing storm yielded cancellation ratios no larger than typical rain cancellation ratios. This indicates the weakness of the cancellation ratio as a sole hail discriminant. Atlas and Wexler <sup>(7)</sup> determined that comparative reflectivity measurements in horizontal and vertical polarization were at least as good as cancellation ratio in hail discrimination.

Circular depolarization ratios (CDR's) less than -23 dB are never associated with hail. CDR's of greater than -14 dB are usually associated with hail; however, some CDR's as large as -7 dB have been associated only with rain. One factor affecting the value of CDR as a hail detecting parameter is the considerable propagation effect exerted on both the transmitted and reflected waves in heavy rain, resulting in an increase in the observed CDR with range. Thus the CDR is of limited value as a sole discriminant of hail.

On the basis of these measurements, it appears that cancellation ratio and differential reflectivity demonstrated limited success as hail detection parameters. Single-parameter hail detection in general is not as effective as the more successful two- and three-parameter methods.

Thermodynamic phase discrimination of the more tenuous clouds may be best achieved by lidar LDR measurements. Clouds consisting solely of liquid

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(7) Atlas, D., and Wexler, R., 1963: Backscatter by Oblate Ice Spheroids. J. Atmos. Sci., 20, 48-61.

water droplets yield lidar LDR's of less than about 0.03. Clouds consisting solely of ice crystals yield LDR's greater than about 0.3, commonly from 0.5 to 0.8, and on occasion, when the crystals are preferentially oriented, greater than 1.0. LDR's between 0.1 and 0.3 are indicative of mixtures of solid and liquid phase cloud particles. A certain amount of measured LDR will be due to multiple scattering among the cloud particles in the volume interrogated. This multiple scattering contribution to measured LDR increases with lidar beamwidth, particle number density, particle size, and range (since the interrogated volume increases as the square of range). Lidar beamwidths of less than about 10 mrad must be used in measuring LDR's for regions of particle densities greater than  $100 \text{ cm}^{-3}$  in order to keep the multiple scattering contribution to the LDR below about 0.04, for a cloud height of about 1000 m, <sup>(8)</sup> based on theoretical calculations illustrated in Figure 1. An obvious limitation on the use of lidar results from its severe attenuation by precipitation and dense clouds.

The best known and probably the most reliable two-parameter method of radar hydrometeor phase discrimination is the combined use of CDR and reflectivity first described by Barge <sup>(9,10)</sup> as illustrated in Fig. 2. For reflectivities less than 30 dB only rain or shot-sized hail (diameter less than 5 mm) were observed at the earth's surface. For reflectivities between 30 and 50 dBZ the likelihood of hail increases with the value of the CDR. In the 30 to 50 dBZ region the hail zone is separated from the rain zone by a line approximately defined by  $10 \log_{10} \text{CDR} = (-.3) \times (10 \log_{10} Z) - 3$ . Those storm regions

<sup>(8)</sup> Liou, K.-N., and Schotland, R. M., 1971: Multiple Backscattering and Depolarization from Water Clouds for a Pulsed Lidar System. J. Atmos. Sci., 28, 772-784.

<sup>(9)</sup> Barge, B. L., 1972: Hail Detection with a Polarization Diversity Radar. Sci Rept. MW-71, Stormy Weather Group, McGill Univ., Montreal.

<sup>(10)</sup> Barge, B. L., 1974: Polarization Measurements of Precipitation Backscatter in Alberta. J. Rech Atmos., 8, 163-173.

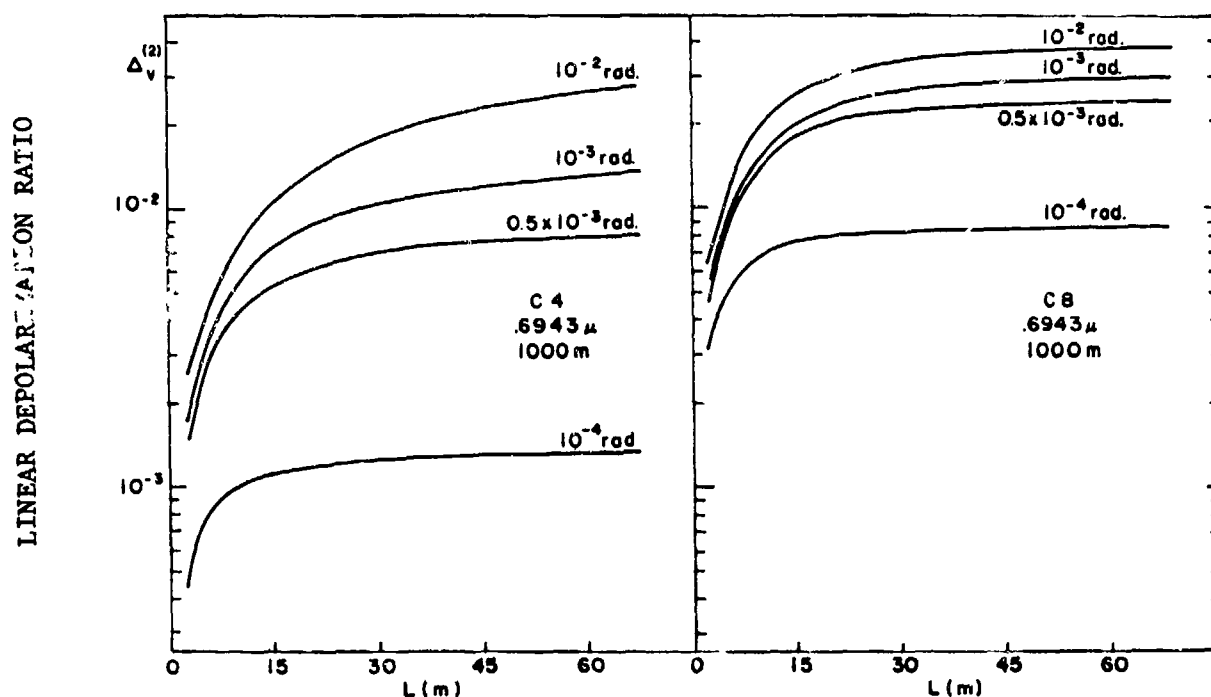
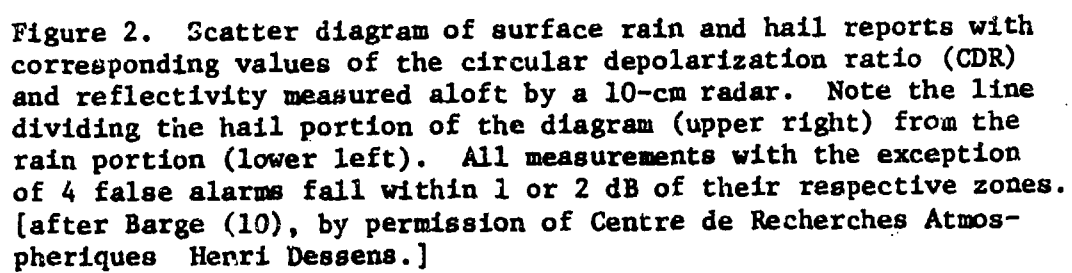


Figure 1. Lidar linear depolarization ratio (due to multiple scattering) for two cloud models, C4 and C8, as function of penetration distance  $L$  into the cloud, with receiver beam widths of  $10^{-2}$ ,  $10^{-3}$ ,  $0.5 \times 10^{-3}$  and  $10^{-4}$  rad. Particles are assumed liquid and spherical, with a number density of  $100 \text{ cm}^{-3}$ . Altitude of cloud base is 1000 m. [after Liou and Schofield (8), by permission of American Meteorological Society.]



having CDR's above that line probably contain large hail and those storm regions having CDR's below that line probably contain no hail larger than shot-size. Of nearly a hundred storm observations made by Barge, there were only about 4 false alarms and no failures to detect hail, as may be seen from Figure 2. Some of the false alarms could be explained as due to hail aloft which melted before reaching the surface. This method of thermodynamic phase discrimination has been well documented only for identification of hail in heavy rain. It has not been used in a systematic way for discrimination of ice crystals and water drops in clouds, but the successful use of LDR for this purpose indicates that more generalized phase discrimination by means of CDR and reflectivity is possible.

The magnitude of cross-correlation  $|\rho|$  between the two receiver channels, also referred to as the percent correlation, may be taken as an indication of the degree of common alignment of the hydrometeors producing the backscatter. Small values of  $|\rho|$  indicate backscatter by particles with little common orientation, whereas larger values of  $|\rho|$  may be taken to indicate a large fraction of preferentially oriented scatterers. Rain drops, which tend to fall as oblate spheroids due to aerodynamic forces, usually produce high values of  $|\rho|$ . Hailstones, which may tumble due to their irregular shape, usually produce lower values of  $|\rho|$ . These characteristics were documented by Hendry et al <sup>(11)</sup> and illustrated in Figure 3. These results suggest the possibility that the percent correlation could be used in conjunction with the reflectivity and depolarization ratio to provide an even more effective technique of identifying hail. Hendry et al <sup>(11)</sup> documented the use of circular depolarization

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<sup>(11)</sup> Hendry, A., McCormick, G. C., and Barge, B. L., 1976: The Degree of Common Orientation of Hydrometeors Observed by Polarization Diversity Radars. J. Appl. Meteor., 15, 633-640.



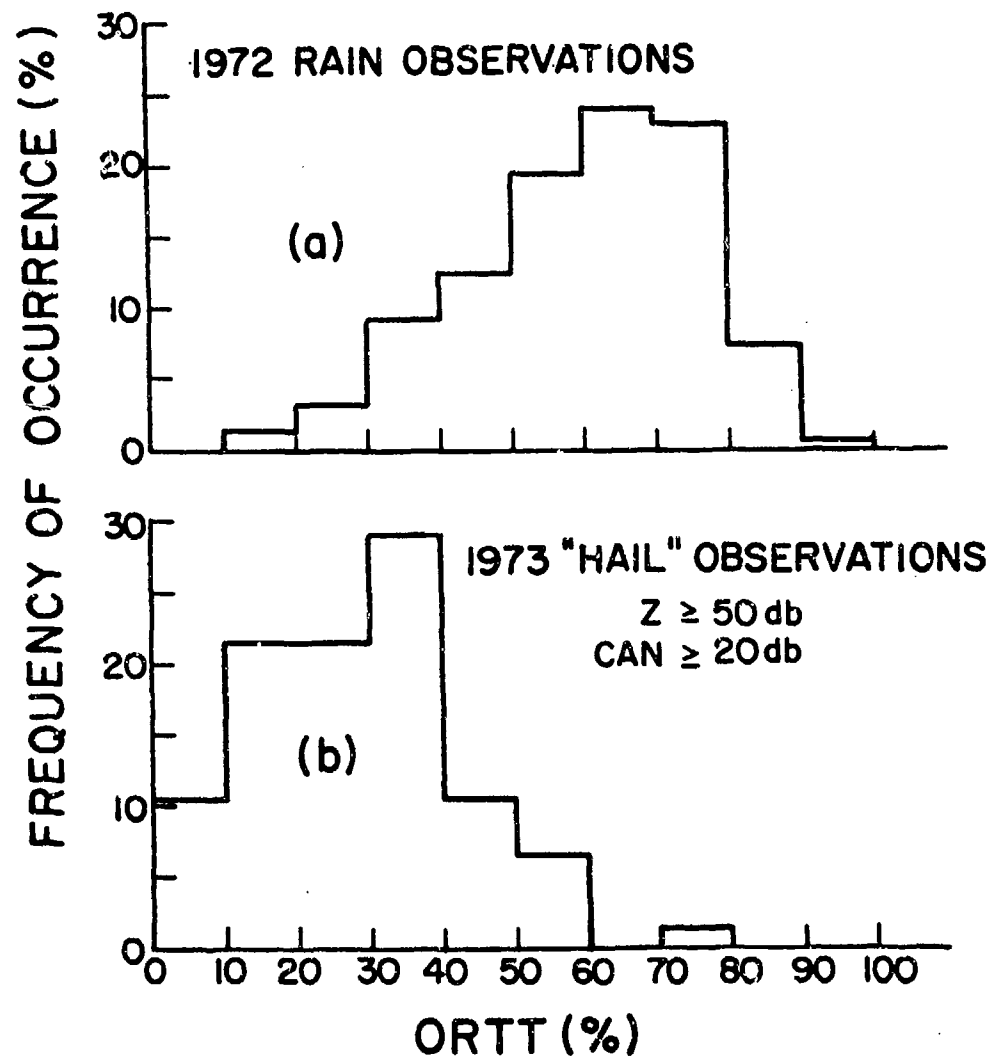


Figure 3. Frequency distributions of percent correlation (designated ORTT) measured by 10-cm radar in Alberta: (a) observations at least 1.5 km below the melting level, (b) "hail" observations based on reflectivity greater than 50 dBZ and CDR greater than -20 dB. [after Hendry et al (11), by permission of American Meteorological Society.]

ratio and percent correlation at 1.8 cm wavelength for identifying light rain, heavy rain, and snow. They found that light rain was associated with low CDR and high percent correlation, heavy rain with moderate CDR and high  $|\rho|$ , and snow with low CDR and low  $|\rho|$ . These characteristics are generally consistent with the physical description of rain as a highly oriented medium, with average ellipticity increasing with rainfall rate due to the presence of more large drops. The significance of the low CDR derived from snow backscatter is uncertain, as one would expect higher CDR from the presumed nonspherical scatterers. An important exception to the association of low  $|\rho|$  with snow is discussed in Subsection II-B below. The percent correlation, like the CDR, is strongly affected by propagation, particularly in heavy rain and at shorter wavelengths due to the increase in both differential attenuation and differential phase shift with rainfall rate and with radar frequency. In some cases the propagation effects can be identified and compensated in the interpretation of data, but in most cases these effects establish upper limits to the water content of clouds or precipitation in which the thermodynamic phase discrimination is valid.

The depolarization ratio (microwave or optical, linear or circular) is moderately effective in discriminating solid hydrometeors from liquid in a wide variety of situations. There is an intermediate region within which the depolarization ratio does not yield an unambiguous identification. This region typically corresponds to a mixture of solid and liquid hydrometeors. Since hail usually exists with rain in a storm, the depolarization ratio alone does not provide an effective discriminant of hail. The most effective identification of thermodynamic phase is obtained from the joint use of reflectivity, depolarization ratio, and percent correlation. Propagation effects and hydrometeor backscatter cross-section, which are wavelength-dependent, impose upper

and lower limits to the size of hydrometeors and the water content or rainfall rate for which phase discrimination can be accomplished at any given wavelength. At long wavelengths (10 cm, for example), propagation effects are minimized, but the scattering cross-section limits measurements to precipitation-sized hydrometeors unless very high power is transmitted. At 1.8 cm, on the other hand, snow and small liquid hydrometeors may be detected, but propagation effects severely limit the accuracy of measurement of backscatter parameters in moderate rainfall.

#### B. SHAPE AND SIZE

It should be pointed out here that the determination of thermodynamic phase is based essentially on the measurement of hydrometeor ellipticity. Spherical and near-spherical scatterers, such as small rain drops, produce low depolarization ratios. Ice crystals, large aerodynamically distorted rain drops, and aspherical hail stones produce much greater depolarization.

Rain drop ellipticity can be specified by the axial ratio  $a/b$  which has been calculated by Pruppacher and Pitter <sup>(12)</sup>. For drops in the Rayleigh scattering region the circular depolarization ratio and the differential reflectivity (between orthogonal linear polarizations) depend only on the axial ratio, which is the principal parameter of rain drop shape. The dependence of CDR on rain drop size, derived by McCormick and Hendry <sup>(13)</sup> and Warner and Rogers <sup>(14)</sup> is shown in Figure 4. Differential reflectivity

(12) Pruppacher, H. R., and Pitter, R. L., 1971: A Semi-Empirical Determination of the Shape of Cloud and Rain Drops. J. Atmos. Sci., 28, 86-94.

(13) McCormick, G. C., and Hendry, A., 1975: Principles for the Radar Determination of the Polarization Properties of Precipitation. Radio Sci., 10, 421-434.

(14) Warner, C., and Rogers, R. R., 1977: Polarization-Diversity Radar: Two Theoretical Studies. Sci. Rept. MW-90, Stormy Weather Group, McGill University, Montreal.

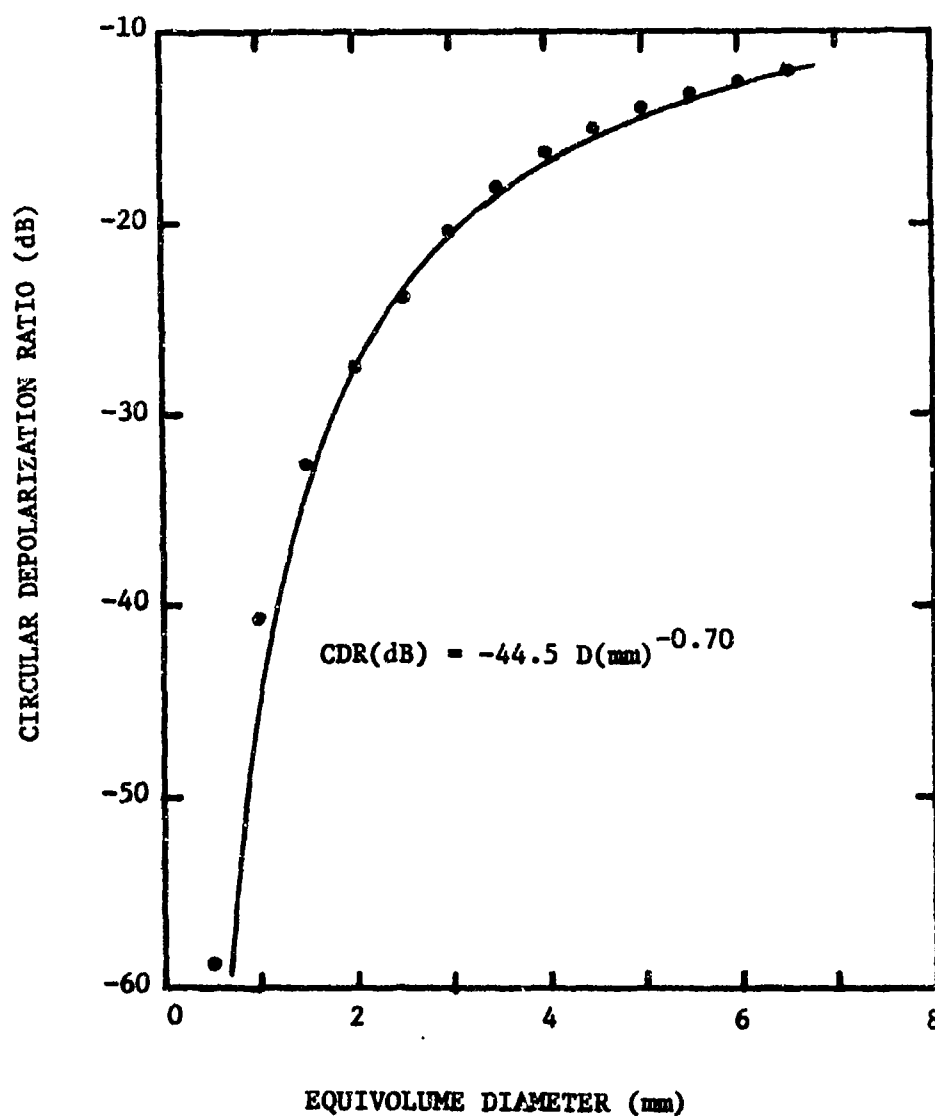


Figure 4. Circular depolarization ratio as a function of rain drop diameter for a single drop viewed at incidence perpendicular to its symmetry axis. Diameter is that of a sphere of equivalent volume. Points represent calculations of McCormick and Hendry (13); line corresponds to the model of Warner and Rogers (14).

is a more reliable indicator of rain drop ellipticity since it is less subject to degradation by differential propagation effects. The rainfall rate measurement technique discussed in Section III is based on the use of differential reflectivity as a measure of average reflectivity-weighted ellipticity of the scattering array and hence a measure of a drop size parameter. There is good reason to believe that the circular depolarization ratio or differential reflectivity can be successfully applied to the determination of rain drop shape, but a quantitative evaluation of such an application must await the results of field implementation. Linear depolarization ratio does not provide a reliable measure of the shape of rain drops because of its dependence on their orientation.

More uncertainty exists in the identification of shapes and sizes of ice crystals, i.e., the crystal habit. Radar depolarization observations have been related to "snow" in general with no more specific designation, and few observations have been reported. At 10 cm the reflectivity of snow flakes and ice crystals is small, and the orthogonal component of the received signal is generally near the receiver noise level. At 1.8 cm the scattering cross-sections of snow and ice crystals are larger, but few radar measurements have been made in conjunction with in situ sampling of clouds. There is a possibility for distinguishing among certain ice crystal forms by means of polarization-diversity lidar. A method used by Sassen <sup>(15)</sup> to identify "plates", "thick plates", "columns", and "needles" in the laboratory involved determining the ratio of the peak return observed in the orthogonal channel to the peak return in the main channel. While the components so measured

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(15) Sassen, K., 1977: Ice Crystal Habit Discrimination with the Optical Backscatter Depolarization Technique. J. Appl. Meteor., 16, 425-431.

do not constitute a true depolarization ratio, they may be expected to be related to depolarization ratios that would be observed in the atmosphere. The values of the ratio so measured were lowest for plate crystals, and successively higher for thick plates and columns. Sassen noted that, while the crystal habit could be identified from the interrogation of individual crystals, it cannot be identified on the basis of linear depolarization ratios from sampling of large numbers of crystals, as would be the case in the atmosphere. Such a categorical statement seems to us to be overly pessimistic, unless one takes it strictly to refer to the use of LDR as a sole discriminant. The prospects of measuring absolute optical reflectivity of ice crystal clouds as well as the  $45^\circ$  polarization component admit the possibility of discriminating at least some shapes of ice crystals.

Another lidar LDR technique of gaining hydrometeor shape information is through observation and measurement of the lidar LDR bright band phenomenon associated with melting snow flakes or graupel<sup>(16)</sup>. LDR's of about 0.5 are observed for falling snowflakes until they descend through the melting layer where their crystal structures collapse gradually in such a way that the inter-crystal reflections (and hence depolarization) are increased. The LDR will increase to a maximum value about 0.7 and then decrease sharply as total melting occurs and the snow flake becomes a liquid water droplet. This lidar LDR bright band observation is a reliable method of detecting a thermodynamic phase transition, and can be readily implemented in field observations. It allows the discrimination between crystalline hydrometeors such as dendrite snowflakes and the more compact ice forms such as graupel, by

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(16) Sassen, K., 1976: Polarization-Diversity Lidar Returns from Virga and Precipitation: Anomalies and the Bright Band Analogy. J. Appl. Meteor., 15, 292-300.

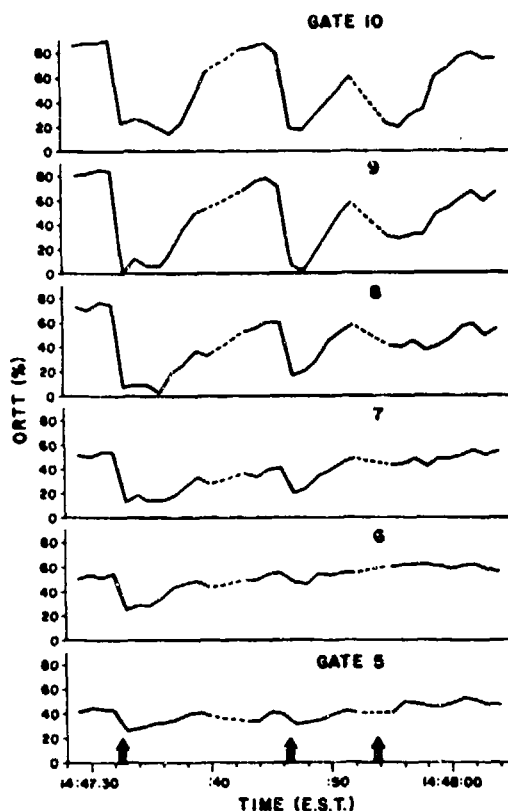
observation and interpretation of the melting process (an "extrinsic" approach) as distinguished from the measurement of backscatter parameters of a discrete sampling volume (an "intrinsic" approach).

Another possible application of the "extrinsic" approach to hydrometeor shape identification is illustrated by observations<sup>(17,18)</sup> of the alignment of particles near the tops of thunderstorms. Figure 5 shows the existence of two modes of behavior of ice crystals in the presence of time-varying electric fields. In each case the sudden change of percent correlation is thought to be associated with an electrical discharge, and the preceding gradual change is associated with the gradual increase of the electric field strength. In one case the "neutral" condition is one of random orientation, with low correlation. In the other case the "neutral" condition is one of high orientation, suggesting the presence of a crystal habit such as plates which are strongly oriented by aerodynamic forces. It is not understood at present how the electric and aerodynamic forces interact, nor why the increasing electric field should act to disorient the crystals. Further investigation of these phenomena should involve improved documentation of electrical activity. In situ sampling of ice crystals would be highly desirable, although such sampling is contingent on considerations of aircraft safety. At the least, the statistics of these occurrences should be developed, as it is not known at present whether one or the other mode of behavior of the

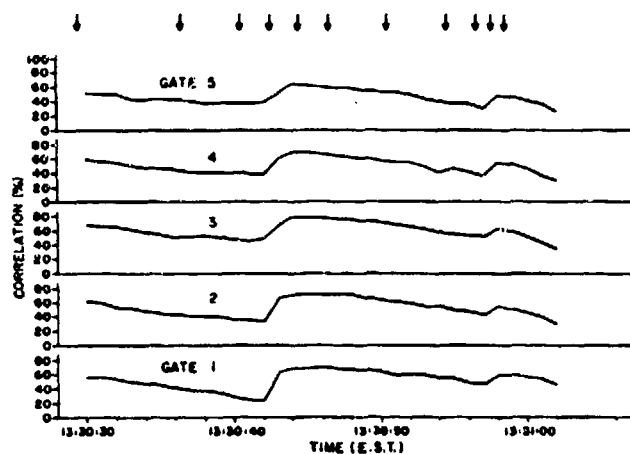
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(17) McCormick, G. C., and Hendry, A., 1976: Radar Observations of the Alignment of Precipitation Particles by Electrostatic Fields in Thunderstorms. Preprints 17th Conf. Radar Meteor., Amer. Meteor. Soc., Boston, 161-167.

(18) Hendry, A., and McCormick, G. C., 1976: Radar Observations of the Alignment of Precipitation Particles by Electrostatic Fields in Thunderstorms. J. Geophys. Res., 81, 5353-5357.



(a)



(b)

Figure 5. Percent correlation (ORTT) measured in adjacent range gates by a 16.5-GHz radar. (a) Slant range 15.4-17.9 km, height 7.8-9.0 km. Correlation increases gradually and drops sharply at 1447:33, 1447:46, and about 1447:54. (b) Slant range 16.0-17.9 km, height 5.8-6.5 km. Correlation decreases gradually and increases sharply at 1330:42 and 1330:58. Lightning discharges recorded by a 150-kHz receiver and indicated by arrows, [(a) after McCormick and Hendry (17), (b) after Hendry and McCormick (18), by permission of American Geophysical Union].



correlation is more frequent or whether either one always occurs in a thunderstorm.

The discrimination of spherical and non-spherical hydrometeors appears to be possible under a fairly wide range of conditions, provided that there is a detectable signal level in the orthogonal receiver channel. Since individual rain drops have circular depolarization ratios of -12 dB or less, higher values of CDR obtained from backscatter measurements may always be taken to indicate the presence of ice particles, if propagation effects can be neglected. If the scattering medium is known to be rain, the CDR provides a direct measure of the reflectivity-weighted ellipticity of the drops, and hence an indirect measure of their size. Similar measurement of the ellipticity of ice crystals is possible, although the unambiguous identification of crystal habit is not generally possible. Some progress has been achieved in this direction through the careful interpretation of temporal or spatial variations of backscatter parameters.

### C. ORIENTATION

The orientation of aspherical hydrometeors relative to the line of sight of a radar can, in principle, be derived by direct measurement of the phase angle between the two components of the received signal. This measurement is reliable for the stated purpose only in the absence of propagation effects, which can result in apparent rotation of the orientation axis with range. The hydrometeor orientation as a parameter is of greatest interest in defining the propagation characteristics of the atmosphere, e.g., for determining the orientation of transmission of optimum elliptical polarization for penetration of rain. In the absence of propagation effects, or at close range, the measurement of the relative phase angle with alternate transmission of right and left circularly polarized signals yields an

unbiased measure of the orientation of the scattering hydrometeors. This technique was used by Hendry and McCormick<sup>(19)</sup>, who documented the tendency for rain drops to be vertically oriented. Additional measurements also indicated a greater spread in the distribution of orientation angles with higher surface wind speed. One could infer increased turbulence from the increased randomness of the scattering medium in such cases. Orientation angles have not been measured by lidar, but we believe that the simultaneous reception of parallel, perpendicular, and 45° polarized backscatter components would define the orientation of the backscattered elliptical polarization and thus yield information analogous to that provided by the relative phase of backscattered microwave signals.

The percent correlation, described above, is a valuable adjunct to the relative phase angle in that it indicates the fraction of scatterers that have the measured orientation angle. Its application in the identification of different hydrometeor types has already been discussed. For determining the propagation characteristics of clouds or precipitation the percent correlation determines the significance of the measured orientation. In rain, for example, the orientation angle is determined to be near zero in most cases and the percent correlation is large, implying a strongly oriented medium. In such cases, where propagation effects preclude direct measurement of orientation angle except at close range, the complex cross-correlation function can be used to obtain the differential propagation parameters of the medium. This use of radar backscatter measurements is discussed further in Section V.

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(19) Hendry, A., and McCormick, G. C., 1971: Polarization Properties of Precipitation Scattering. Bull. Radio Elect. Engr. Div., Nat'l Res. Council, 21, 9-20.

### III. DIRECT MEASUREMENT OF RAINFALL RATE

The measurement of rainfall rate by a single-channel fixed polarization radar involves the use of a statistical relationship between reflectivity factor  $Z$ , which is the sixth moment of the rain drop size distribution, and the rainfall rate  $R$ , which is the fall velocity weighted third moment of the distribution. The  $Z$ - $R$  relationship is determined by drop size distribution, since a given rainfall rate comprising many small drops has a much lower reflectivity than the same rainfall rate comprising a smaller number of large drops. Thus a variety of  $Z$ - $R$  equations have been derived from theory and measurements for different types of rain, e.g., stratiform, orographic, convective shower, thunderstorm, and different geographical areas, e.g., tropical, sub-tropical, mid-latitude. Two sources of uncertainty are evident in this procedure, one associated with the selection of a particular  $Z$ - $R$  equation and the other associated with the statistical fluctuations inherent in all such equations due to the variations of drop size distributions within a particular rain storm or from one storm to another of the same type.

Considerable improvement in accuracy of rainfall measurement could be realized if the drop size distribution in each radar resolution cell could be determined. One approach to this problem is to assume that the distribution is exponential and therefore characterized by two parameters:

$$N(D) = N_0 e^{-\Lambda D}$$

If one can relate two radar-measurable parameters to the two parameters of the distribution, then the rainfall rate or liquid water content can be obtained directly, i.e., without recourse to a statistical Z-R equation. The use of differential reflectivity measurements at two wavelengths for this purpose was discussed by Atlas and Ulbrich<sup>(20)</sup>. Seliga and Bringi<sup>(21)</sup> suggested the use of differential reflectivity at orthogonal polarizations together with the absolute reflectivity to yield the two parameters of the drop size distribution.

The determination of the median volume diameter of the rain drops is based on the size-dependent distortion of the drops from spheres to oblate spheroids and on their tendency to fall with their axes of revolution oriented vertically. The relative magnitude of reflectivity in vertical and horizontal planes thus provide a measure of the effective (reflectivity-weighted) ellipticity of the scattering medium and hence of a scale size corresponding to that ellipticity. Seliga and Bringi<sup>(21)</sup> showed that by using an assumed exponential drop size distribution and a known ellipticity-size relation the differential reflectivity, i.e., the ratio of backscattered power in the main (parallel) channel when horizontal polarization was transmitted ( $Z_H$ ) to that in the main channel when vertical polarization was transmitted ( $Z_V$ ), could be expressed as a function of  $D_0$ , the median volume diameter defined by  $D_0 = 3.67/\Lambda$ . Since the absolute reflectivity in either polarization

(20)

Atlas, D., and Ulbrich, C. W., 1974: The Physical Basis for Attenuation-Rainfall Relationships and the Measurement of Rainfall Parameters by Combined Attenuation and Radar Methods. J. Rech. Atmos., 8, 275-298.

(21)

Seliga, T. A., and Bringi, V. N., 1976: Potential Use of Radar Differential Reflectivity Measurements at Orthogonal Polarizations for Measuring Precipitation. J. Appl. Meteor., 15, 69-76.

plane is defined by the two parameters of the assumed exponential distribution function, the measurement of either of these in addition to the differential reflectivity provides an estimate of both parameters of the distribution. The rainfall rate or liquid water content can then be obtained directly from the drop size distribution.

An alternative approach to the radar measurement would be to use circular polarization and a dual-channel receiver. Since the circular depolarization ratio provides a measure of effective ellipticity analogous to that provided by the differential reflectivity  $Z_H/Z_V$  it can be used to determine the median volume diameter. The main channel reflectivity can then be used to determine the coefficient  $N_o$ . The Theoretical and experimental work of Barge <sup>(9)</sup> and Humphries <sup>(22)</sup> indicates that this approach may not be feasible due to propagation effects. Even at long wavelengths (10 cm) differential phase shift can significantly alter the polarization state of the radar signal and lead to large measured values of circular depolarization ratio. This is particularly true when the signal propagates through a region of heavy rain. Signals with linear polarizations aligned with the anisotropy axes of a rain medium propagate with little or no depolarization. Because rain drops tend to be oriented with their symmetry axes vertical, signals polarized in horizontal and vertical planes are most effective for penetrating the rain. Thus the differential reflectivity is likely to provide a more reliable measure of  $D_o$  than the circular depolarization ratio. Seliga and Bringi suggested dual-channel reception as preferable to single channel reception, but this involved reception of linearly polarized backscatter components from transmission of equal signals in the two planes. For this purpose the transmission could thus be of any ellipticity (from linear to circular) with a  $45^\circ$  orientation.

The advantage of the differential reflectivity technique of

(22)

Humphries, R. G., 1974: Depolarization Effects at 3 GHz due to Rain. Sci. Rept. MW-82, Stormy Weather Group, McGill Univ., Montreal.

measuring rainfall is that the parameters of the drop size distribution are determined at every radar resolution cell. Variations of the drop size distribution within a rain storm are thus accommodated, and the scatter of  $\pm 2.5$  dB typically observed for a set of reflectivity and rainfall measurements about a best-fit Z-R correlation is thereby eliminated. On the other hand an uncertainty is introduced by the assumption of an exponential form of the drop size distribution. The determination of  $D_0$  is based essentially on the size distribution of the drops that contribute most to the reflectivity, i.e., between about 1.5 and 5 mm in heavy rain. In this example, if the drop size distribution is exponential, then nearly half the water content is contained in drops smaller than 1.5 mm. If the drop size distribution is more nearly log normal, as is sometimes observed in thunderstorms,<sup>(23)</sup> then the reflectivity characteristics can be nearly unchanged relative to the assumed exponential distribution function while the water content or rainfall rate can be as much as 50% less than that due to an exponential distribution. One is left with a dilemma, in that in stratiform rain, where the exponential drop size distribution is most nearly valid, variations in drop size distribution are less significant and the traditional approach to rainfall measurement is adequate for many purposes. In thunderstorms, on the other hand, where wide variations in drop size distribution make the use of a single Z-R equation particularly suspect, there are also significant deviations from exponential shape, so that

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(23)

Martner, B. E., 1975: Z-R and Z-W Relations from Drop Size Measurements in High Plains Thunderstorms. Preprints 9th Conf. Severe Local Storms. Amer. Meteor. Soc., Boston, 307-310.

rainfall rate computations based on the differential reflectivity technique can easily overestimate the true rainfall rate by a factor of two (3 dB).

An additional uncertainty factor is introduced by the statistical fluctuations of the backscattered signals. The effects of these fluctuations on the accuracy of determining  $D_0$  and  $N_0$  were addressed by Seliga and Bringi, using the best case measurement of  $Z_H/Z_V$  by simultaneous transmission in both planes and reception in a dual-channel receiver. If the differential reflectivity is measured with an uncertainty of  $\pm 0.2$  dB,  $D_0$  is determined with an uncertainty of about 0.15 mm between 0.5 and 3.0 mm. With absolute reflectivity measured with an accuracy of  $\pm 1.0$  dB (including both statistical fluctuations and system calibration factors) they obtained an uncertainty of rainfall measurement of about  $\pm 5.7$  dB for  $D_0 = 1.5$  mm (moderate to heavy rain) decreasing to  $\pm 2.9$  dB for  $D_0$  greater than 2.5 mm (intense rain). The former uncertainty is slightly better than that which one would obtain with the traditional method and the arbitrary use of the Marshall-Palmer Z-R equation. If Z-R equations appropriate to the type of rain and geographical location are selected, e.g., from those listed by Battan <sup>(24)</sup>, then uncertainty of less than 5 dB can be obtained with the traditional technique. Z-R equations derived from measurements in thunderstorms in various geographical areas yield rainfall rates within about 4 dB of

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Battan, L. J., 1973: Radar Observation of the Atmosphere. Univ. of Chicago Press.

each other through the applicable range of reflectivities. With statistical uncertainty included, one can expect an uncertainty of about 6 dB with the traditional approach. Concurrent measurements of drop size distribution, whereby a local Z-R equation can be obtained, provide a much more accurate measure of rainfall, since the uncertainty is then due only to radar signal fluctuations and to the small spread of data points about the correlation line, for a total of about  $\pm 3$  dB. Thus the differential and absolute reflectivity technique provides rainfall estimates in moderate rain which are comparable to those obtained with the traditional technique, when Z-R equations are carefully chosen. In very heavy and intense rain the differential and absolute reflectivity technique may yield somewhat better estimates, despite the tendency to overestimate the rainfall rate.

An alternate method of implementation suggested by Seliga and Bringi <sup>(21)</sup> and subsequently used by them in field experiments involves the measurement of reflectivity in horizontal and vertical planes sequentially by alternating the transmitted polarization and using a single-channel receiver. In this case the differential reflectivity is subject to the uncertainties of both of the individual reflectivity measurements, or about  $\pm 1.0$  dB in the best case. Using the uncertainty formulations presented by Seliga and Bringi we determine an uncertainty in rainfall rate of about 10 dB for  $D_0 = 1.5$  mm and about 6 dB for  $D_0$  greater than 2.5 mm. While this implementation yields rainfall estimates that are no more accurate than those obtained by the traditional technique, it is valuable for identifying and evaluating particular sources of uncertainties in the measurements and data handling procedures.



These uncertainties may then be amenable to reduction by modifications in the analytical procedures. We have determined through a private inquiry that Seliga and Bringi are satisfied with the results of their experimental program. The results appear to have met objections which had been raised concerning the possibility of measuring reflectivity with the accuracy they required.

#### IV. DOPPLER RADAR PULSE-PAIR CODING

The use of orthogonal linear polarizations for coding of coherent radar pulses was suggested by Doviak and Sirmans (25) as a way of circumventing the range-velocity ambiguity. This ambiguity arises from the dependence of both the maximum unambiguous range  $r_{\max}$  and the maximum unambiguous velocity  $v_{\max}$  on the pulse repetition rate.

$$r_{\max} = \frac{c}{2 \times \text{PRF}}$$

$$v_{\max} = \text{PRF} \times \lambda / 4$$

Combining these equations yields

$$r_{\max} v_{\max} = \frac{c \lambda}{8}$$

Thus if a pulse repetition rate is chosen to provide a reasonable maximum range for surveillance, 150 km, for example, then unambiguous velocity measurement is limited to  $\pm 25 \text{ m sec}^{-1}$  at 10 cm wavelength and  $\pm 8.0 \text{ m sec}^{-1}$  at 3.2 cm. It has been suggested that if pairs of closely spaced pulses can be transmitted at intervals corresponding to conventional interpulse periods the intra-pair spacing  $T_1$  will determine the maximum unambiguous velocity and the inter-pair spacing  $T_2$  will determine the maximum unambiguous range. The resulting signals can then be processed by

(25)

Doviak, R. J., and Sirmans, D., 1972: Doppler Radar with Polarization-Diversity. J. Atmos. Sci., 30, 737-738.

the "pulse pair" technique to provide an estimate of the auto-correlation function and hence of the mean Doppler velocity. The double-pulsing technique can be implemented in a single-channel radar provided (1) that the intra-pair spacing  $T_1$  be greater than the time required for two-way propagation through a storm and (2) that multiple storms on a given radial be separated by a distance greater than  $cT_1/2$ . These conditions imply that the backscatter signals from the two pulses do not overlap in time in the receiver. Such an implementation was discussed by Campbell and Strauch<sup>(26)</sup>.

The above restrictions may be relaxed if the pulses constituting each pair are coded, so that the received signals can be separated even though they may overlap in time at the receiver. Polarization diversity provides a means of achieving this objective, since the two pulses of each pair can be transmitted with orthogonal polarizations and the received signal can be separated into two correspondingly polarized components. The success of the technique depends essentially on the degree of isolation that can be achieved between the two signals. Doviak and Sirmans indicated that the limiting factor is the coupling between the two signals by the atmosphere through depolarization in propagation and scattering. They cite earlier calculations and measurements indicating linear depolarization ratios less than -20 dB in rain at wavelengths greater than 3 cm.

(26)

Campbell, W.C., and Strauch, R. G., 1976: Meteorological Doppler Radar with Double Pulse Transmission. Preprints 17th Conf. Radar Meteor., Amer. Meteor. Soc., Boston, 42-44.

The effect of this coupling is to introduce a noise component into one receiver channel due to depolarization of the signal in the opposite channel. The depolarized component is of little significance unless the signal in one channel is much larger than that in the other. If a region of a storm having reflectivity  $Z_1$  is separated by a distance  $cT_1/2$  from a region having a reflectivity  $Z_2 = Z_1 + 20$  dB, then signals from these regions will arrive at the receiver simultaneously on opposite channels and if the coupling is -20 dB then the weaker of the two signals will include equal contributions due to backscatter from region 1 and to cross-polarization coupling from region 2. If the separation between successive pulse pairs  $T_2$  is greater than the decorrelation time of the echoes, then the cross-polarized component will be uncorrelated from pair to pair, and by increasing the number of pairs used in computing the auto-correlation function one can obtain a satisfactory estimate of the mean velocity.

An additional aspect of the propagation problem which Doviak and Sirmans did not address is the anisotropy of rain as a propagation medium, which leads to differential phase shift and differential attenuation of vertically and horizontally polarized signals. Differential attenuation is negligible at 10 cm wavelength, but can amount to a few tenths of a decibel per kilometer at 5 cm and up to 1 dB  $\text{km}^{-1}$  in intense rain (100 mm  $\text{hr}^{-1}$ ) at 3 cm. Differential phase shift is more important, ranging from 4 deg  $\text{km}^{-1}$  in intense rain at 10 cm to 10 deg  $\text{km}^{-1}$  at 3 cm. Differential propagation effects can be compensated by alternating the order of polarization in each pair, so that the phase errors in successive pulses are averaged out. The increased variance of the mean velocity estimate will require somewhat longer averaging intervals in cases of large differential

phase shift. These effects will not bias the estimate of the autocorrelation function if alternating polarization is used.

The polarization-diversity pulse-pair technique offers advantages over other techniques for circumventing the range-velocity ambiguity in that it requires a single frequency (no frequency agility), fixed mode of operation (no adjustments in  $T_1$  and  $T_2$  required in real time), and ease of data analysis and interpretation (direct interfacing to existing pulse-pair processing equipment). It does require greater complexity of the transmitter and receiver, due to the requirement of rapid switching of polarization between pulses and the use of a dual-channel coherent receiver. Implementation of the concept is well within the state-of-the-art in radar technology, but the operational advantage over a double-pulsed single-channel radar is probably not sufficient to justify the additional complexity. It would be reasonable and probably beneficial to incorporate this capability into a polarization-diversity radar system designed for a broader set of research objectives.

## V. PROPAGATION PARAMETERS

Much of the theoretical and experimental research that has been done in the area of atmospheric propagation appears at first glance to be difficult to relate to meteorological research. The research reviewed by Hogg and Chu<sup>(27)</sup> and Oguchi<sup>(28)</sup> deals mainly with the large-scale or time-averaged properties of the atmosphere as a propagation medium, and does not immediately relate to the needs of the research meteorologist for measuring the small-scale structure of the atmosphere. For communications systems or other radar applications the need is to specify performance criteria in terms of percent time that the total attenuation or depolarization exceeds given criteria. Designers of these systems are often concerned with techniques such as adaptive polarization for optimizing penetration of precipitation by electromagnetic signals.

These applications involve models of the atmosphere which in turn require basic knowledge of meteorological parameters and processes such as scattering and absorption as functions of hydrometeor shape, size, and orientation and the relationships of these parameters to wind structure and electric fields. The observations of cross-polarization of signals from the ATS-6 satellite by Watson et al<sup>(29)</sup> illustrate this point well, in that by themselves they provide limited

(27)

Hogg, D. C., and Chu, T.-S., 1975: The Role of Rain in Satellite Communications. Proc. IEEE, 63, 1308-1331.

(28)

Oguchi, T. 1975: Rain Depolarization Studies at Centimeter and Millimeter Wavelengths: Theory and Measurement. J. Radio Res. Lab, Japan, 22, 165-211.

(29)

Watson, P. A., McEwan, N. J., Dissanayake, A. W., Haworth, D. P., and Vakili, V. T., 1977: Attenuation and Cross-Polarization Measurements at 20 GHz using the ATS-6 Satellite with Simultaneous Radar Observations. Proc. URSI Symp. Propag. Non-Ionized Media, Ctr. Nat'l. d'Etudes Telecomm., France, 345-350.

meteorological information while they show the need for basic meteorological understanding to explain the observed propagation effects.

Many of the needs of communications systems designers and operators have been met by the many propagation link experiments which have been done at microwave frequencies from a few gigahertz to nearly 100 GHz as well as at infrared and optical frequencies. These results, coupled with rainfall statistics for a given area, may adequately define the propagation medium, particularly for long-term operations.

For short-term microwave and optical applications the small-scale structure of the atmosphere and its variations are of greater significance. Such applications include surveillance for air defense, air traffic control, and weapons guidance, where system outages due to momentary propagation effects can have specific costly or dangerous consequences. Thus there appears to be increasing interest in the magnitude and duration of the extremes of various propagation effects. The nature of these phenomena presents opportunities for significant contributions to microwave propagation applications from meteorological research programs.

The associations of hydrometeor orientation effects with electric fields in thunderstorms by Hendry and McCormick<sup>(18)</sup> and by Watson et al<sup>(29)</sup> and with wind shear by Brussaard<sup>(30)</sup> illustrate these opportunities. The National Research Council of Canada has made substantial progress in relating radar backscatter parameters to propagation effects at 16.5 GHz (1.8 cm). However, in their measurement programs and in many others

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Brussaard, G., 1976: A Meteorological Model for Rain-Induced Cross-Polarization. IEEE Trans. Antennas Propag., AP-24, 5-11.

basic meteorological documentation is limited or lacking. In the case of thunderstorm electric fields the lack can be ascribed to difficulty of measurement. On the other hand, a major deficiency of many propagation measurement programs is the inadequacy of measurements of rainfall rate and drop size distribution. No measurements have yet been published on the effects of wind shear on rain drop canting, but such measurements will require careful documentation of the wind profile as well as the rain drop size distribution.

The use of adaptive polarization offers additional opportunities for the combined efforts of meteorologist and radar engineers. Possible improvements of 5-10 dB in rain "clutter" cancellation <sup>(31)</sup> are discussed further in Section VI.

Bulk propagation parameters as functions of rainfall rate are fairly well documented across the longer-wavelength portion of the microwave spectrum, both by theoretical models and by measurements. Parameters of interest include total attenuation and phase shift and differential attenuation and phase shift between the symmetry axes of the anisotropic propagation medium. Measurements at the shorter millimeter wavelengths are fewer, although effects can be predicted from existing theory which has been confirmed for the longer wavelengths. The greatest needs at present are for improved meteorological documentation in direct measurement programs and for further meteorological research in the atmospheric processes which cause propagation effects of large magnitude and short term. As these effects are better understood, adaptive polarization techniques can be developed to provide short-term local improvement to compensate for them.

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(31)

McCormick, G. C., and Hendry, A., 1972: Results of Precipitation Backscatter Measurements at 1.8 cm with a Polarization Diversity Radar. Preprints 15th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, 35-38.



## VI. CLUTTER SUPPRESSION

Backscatter characteristics of various radar targets have been measured and modeled in many research programs for purposes of discriminating different types of targets. Of particular interest is the possibility of selectively suppressing the backscattered signals from certain targets. In meteorological applications, backscatter from the ground, either in side lobes or the main lobe, constitutes "clutter" signal which degrades the operating capability of the radar at low elevation angles or short range. In non-meteorological applications, such as ground mapping or detection and tracking of vehicles or aircraft, hydrometeors constitute part of the "clutter". Thus a major research effort has been directed to determining the scattering characteristics of hydrometeors relative to natural ground targets or man-made targets, for the purpose of selectively discriminating for or against meteorological backscatter. This section describes the application of polarization-diversity techniques to these operational problems.

### A. SUPPRESSION OF METEOROLOGICAL ECHOES

Early developments in the theory of the polarization characteristics of hydrometeor backscatter revealed that these characteristics could be exploited for the suppression of meteorological echoes relative to ground echoes and vehicular echoes. What this involves essentially is the selective reception of the "orthogonal" component of the backscatter, since the "main" component contains most of the meteorological echo.

Various forms of transmitted polarization have been investigated and compared for this purpose. In the case of linear polarization, a dual-channel system is required, since the polarization of the "orthogonal" component of the received signal is perpendicular to that of the transmitted signal. If circular polarization is transmitted, a single channel system can be used, since in this case the "orthogonal" component of the received signal has the same sense of polarization as the transmitted signal. Early studies<sup>(32)</sup> documented the superiority of circular polarization for this purpose, and subsequent studies have refined the early results and extended them to a wider range of frequencies.

The variability of precipitation and the known ellipticity of rain drops led to the consideration of elliptical and adaptive polarization techniques for improved meteorological clutter suppression. Measurements and computations by McCormick and Hendry<sup>(31)</sup> showed that at 16.5 GHz an improvement of 5 to 10 dB in cancellation ratio could be obtained by means of elliptical polarization. It should be emphasized that this improvement is rather sensitive to rainfall rate. In the example presented by McCormick and Hendry and shown in Figure 6, optimization for a rainfall rate of  $20 \text{ mm hr}^{-1}$  yielded up to 10 dB improvement at that rainfall rate for an intermediate range of target intensities. Improvement decreased to a few dB for intense targets at higher rainfall rate, whereas performance was actually degraded by 10 dB or more for weak targets at rainfall rates less than  $20 \text{ mm hr}^{-1}$ . Such sensitivity to

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(32)

Gent, H., Hunter, I. M., and Robinson, N. P., 1963: Polarization of Radar Echoes, Including Aircraft, Precipitation, and Terrain. Proc. IEEE, 110, 2139-2148.

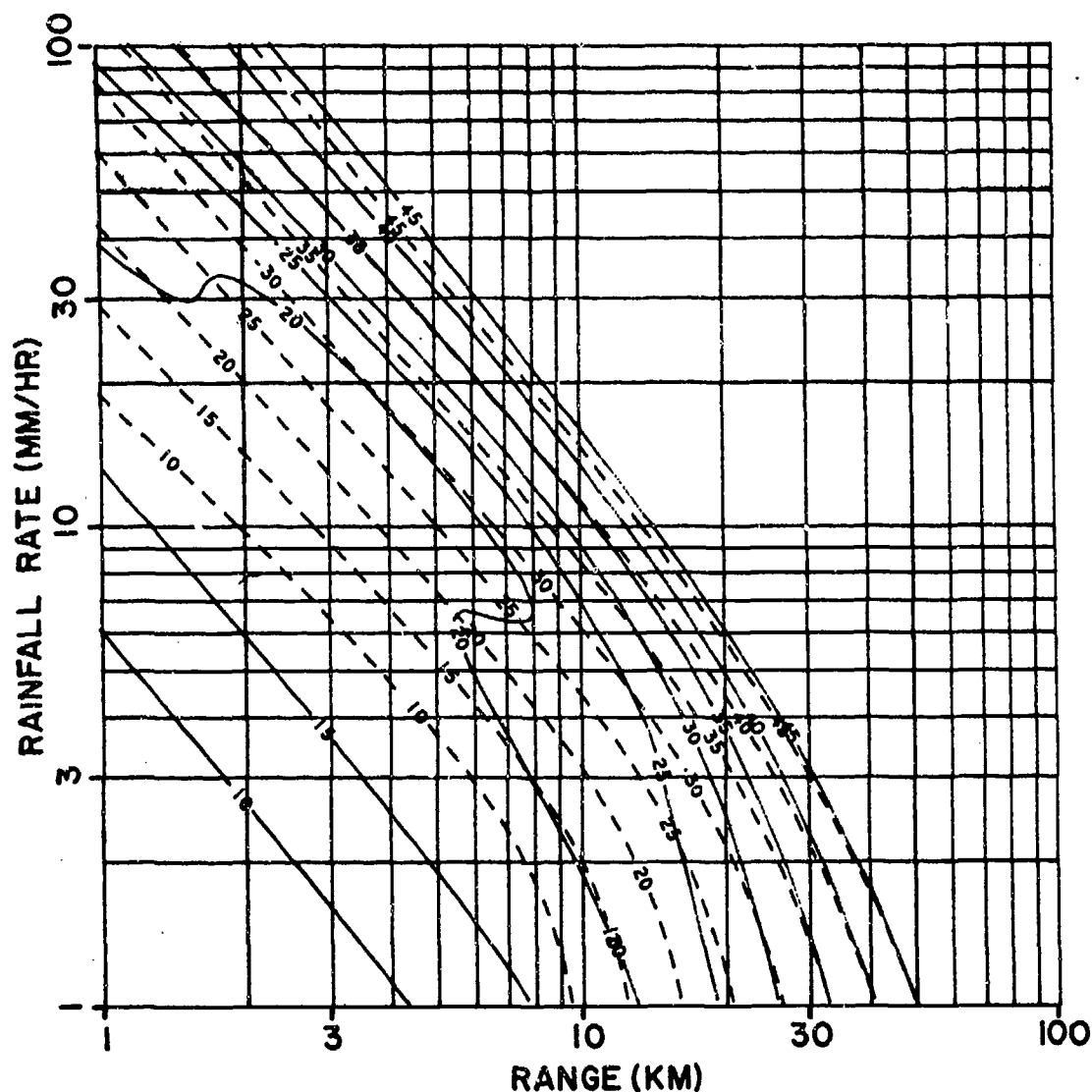


Figure 6. Radar range vs. rainfall rate for a target of given cross section in a rain clutter environment. Solid lines are for optimized elliptical polarization; broken lines are for circular polarization. Optimization is for  $20 \text{ mm hr}^{-1}$  and for specified propagation conditions. Contour parameter is target strength index in dB defined by:

$$S_{\text{dB}} = 10 \log \left[ \frac{P_p + P_n}{P} \frac{\sigma}{\lambda^2} \right]$$

where  $P_p$  is precipitation backscatter,  $P_n$  is receiver noise,  $P$  is target backscatter,  $\sigma$  is target cross section, and  $\lambda$  is radar wavelength [after McCormick and Hendry (31)].

rainfall rate makes the use of elliptical polarization extremely difficult to implement for operational purposes, unless the polarization can be adapted to the rain and target conditions.

Measurements at various frequencies have indicated cancellation ratio of -25 to -30 dB in light rain at frequencies from 1.3 to 16.5 GHz and -17 dB at 35 GHz<sup>(33)</sup>. In the melting layer (bright band) cancellation ratios have been measured at -17 dB for 9.3 GHz and -8 dB for 35 GHz<sup>(32)</sup>. Some confusion is inherent in the comparison of various measurements because of the use of the term "cancellation ratio" by some authors to describe what we refer to as the circular depolarization ratio. Hence the measurements of circular depolarization ratio of -25 to -30 dB in rain and -13 to -15 dB in the melting layer at 2.88 GHz by Humphries<sup>(22)</sup> cannot be compared exactly to some of the foregoing measurements.

Related measurements on non-meteorological targets have documented their polarization characteristics relative to those of precipitation. Cancellation ratio for backscatter from aircraft has been measured as -1 to -2 dB at 35 GHz and -2.5 dB at 9.3 GHz<sup>(32)</sup> and -6 dB at 1.3 GHz<sup>(34)</sup>. Backscattered signals from ground targets tend to be more equally distributed in the two channels so that only about 1 dB loss occurs with circular polarization. This characteristic of ground echoes is useful in suppression of ground echoes relative to meteorological backscatter.

(33)

Nathanson, F. E., 1975: Adaptive Circular Polarization. IEEE Intl. Radar Conf., 221-225.

(34)

Offutt, W. B., 1955: A Review of Circular Polarization as a Means of Precipitation Clutter Suppression and Examples. Proc. Nat'l. Elec. Conf., 11, 94-100.

Recent research in meteorological echo cancellation has focused on the dependence of performance on rainfall rate and other environmental parameters. Peebles<sup>(35)</sup> has computed the cancellation ratio as a function of rainfall rate and radial wind speed for several rain models. These results indicate that greater cancellation (i.e., more strongly negative decibel quantities) are attainable with increasing magnitude of the radial component of the ambient wind. Unfortunately, the physical basis of the model formulation is not clear. Hence the significance of the -45 to -60 dB cancellation ratios he obtained for light rain and wind speeds of 25-30 m sec<sup>-1</sup> is uncertain.

The range dependence of clutter cancellation performance, particularly at short wavelengths, is an important phenomenon which has received limited attention in theoretical and experimental work. Measurements of circular depolarization ratio by Hendry and McCormick<sup>(36)</sup> showed that the ratio is nearly independent of range for rainfall rates of a few millimeters per hour, but increases at 3 to 4 dB km<sup>-1</sup> for rainfall rates of 15 to 75 mm hr<sup>-1</sup>. They discussed the practical problems of optimizing elliptical polarization for greater clutter cancellation, and noted that the deterioration in cancellation with range in heavy rain might best be reduced by the use of a dual-channel linearly polarized radar. Figure 7 illustrates a problem of optimizing elliptical polarization for operation in a fixed polarization mode.

(35)

Peebles, P. Z., 1975: Radar Rain Clutter Cancellation Bounds Using Circular Polarization. IEEE Intl. Radar Conf., 210-214.

(36)

Hendry, A., and McCormick, G. C., 1974: Deterioration of Circular Polarization Clutter Cancellation in Anisotropic Precipitation Media. Electr. Lett., 10, 165-166.

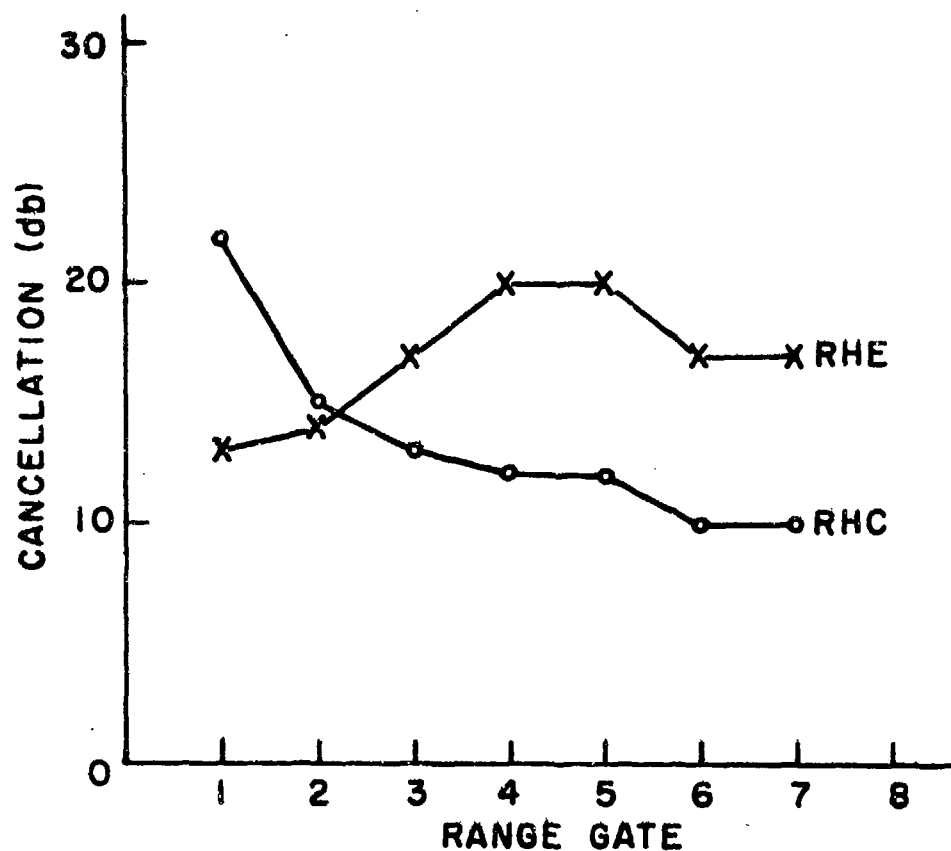


Figure 7. Depolarization ratio (-dB), or cancellation (dB), as a function of range as a result of right hand circular transmission and right hand elliptical transmission at 1.8 cm. Elliptical polarization was optimized for gates 4 and 5; note that depolarization ratio is larger in gate 1 for elliptical polarization, due probably to the presence of more spherical hydrometeors at that range. Range to gate 1 is 3.1 km; gate spacing is 500 m [after Hendry and McCormick (36), by permission of the Institution of Electrical Engineers].

The choice of a radar system for cancellation of meteorological echoes depends on the relative importance of several operational parameters. These include the range at which target detection is required, the rainfall rates in which the system is required to operate, and constraints of size, weight, and complexity of the equipment. Circularly polarized transmission with single channel reception of the same sense of polarization appears to be the best choice for a wide variety of applications. At frequencies greater than about 15 GHz and rainfall rates greater than about  $10 \text{ mm hr}^{-1}$  performance is progressively degraded with range due to propagation effects. In this case the use of adaptive elliptical polarization optimized for a particular range or the use of linear polarization with a dual-channel receiver may be warranted.

Meteorological echo suppression at optical wavelengths has recently received attention<sup>(37)</sup>. Experiments were performed in which a circular polarizer material was placed in the path of a laser beam which was illuminating a volume of steam. In results analogous to those at microwavelengths, the backscattered light with polarization identical to the transmitted polarization was significantly reduced, and a non-specular object partially obscured by steam could be seen more clearly. Although optical systems are limited in range by attenuation in fog and clouds, the selective suppression of backscattered signals from hydrometeors is of significance for improving their short range performance.

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(37)

Boyd, J. T., Kock, W. E., and Yang, S. K., 1977: Circular Polarization at Light Wavelengths. Proc. IEEE, 65, 1218-1219.

## B. SUPPRESSION OF NON-METEOROLOGICAL ECHOES

Because of near-spherical shape of many hydrometeors, the backscattered signal is returned in the main channel of a dual-channel radar. In the case of linear polarization, this is the "parallel" channel, whereas for circular polarization it is opposite to the polarization of the transmitted signal. Polarization characteristics of other types of targets depend on shape and orientation. Man-made objects such as vehicles and buildings tend to return signals in the main channel, particularly when viewed at normal incidence to their flat surfaces, since the reflection is "single bounce". Vegetation, on the other hand, comprises both "odd bounce" scattering elements, which return a signal into the main channel, and "even bounce" scattering elements, which return a signal into the orthogonal channel. Thus it has been suggested that this characteristic of vegetation be used to selectively suppress a significant portion of "ground clutter" encountered on meteorological radar displays at short range and low elevation angles.

Measurements of backscatter from rain and from vegetative ground clutter at Georgia Institute of Technology and elsewhere at 3.2 cm wavelength have confirmed that if circular polarization is transmitted the averaged opposite-sense (main) circular component of the backscatter from rain is 20 dB or more above the averaged same-sense (orthogonal) circular component. Circular depolarization ratios ranging from -15 dB in wet snow to -30 dB in rain have been reported. On the other hand, the circular depolarization ratio of distributed vegetation ranges from -3 to +3 dB. Similar characteristics have been documented at 1.8 cm.



One approach to implementing the ground clutter suppression involves the transmission of circular polarization and reception of orthogonal linear components. In this case the signals due to rain are nearly equal in amplitude but differ in phase by approximately 90 degrees, whereas the signals due to vegetation tend to be independent in phase.

If vertically and horizontally polarized signal components  $E_V$  and  $E_H$  are received these may be represented by the sum of contributions by rain and ground with magnitudes of  $E_r$  and  $E_g$ .

$$E_V = E_r \cos \omega t + E_{gV} \sin (\omega t + \phi_V)$$

$$E_H = E_r \sin \omega t + E_{gH} \sin (\omega t + \phi_H)$$

The horizontal component is delayed 90 deg in phase and mixed with the vertical component to yield a video signal V.

$$V = \frac{E_r^2}{2} + \frac{E_r E_{gH}}{2} \cos \phi_H + \frac{E_r E_{gV}}{2} \sin \phi_V + \frac{E_{gV} E_{gH}}{2} \cos(\phi_V - \phi_H) \\ + \text{terms involving } 2\omega t$$

The higher harmonic terms are filtered out and the signal is averaged to yield an output  $V_o$

$$V_o = \frac{1}{T} \int_0^T V dt = \frac{E_r^2}{2}$$

The latter quantity is proportional to the reflectivity factor Z. This result is based on the assumption that  $\phi_H$  and  $\phi_V$  are independent uniformly distributed random functions of time. The time required for the integration is several tenths of a second, as this is the fluctuation time scale of the orthogonally polarized return signals from ground clutter. In operational use this would require antenna scan rates of about 2 RPM, which is reasonable for meteorological research radar applications, but might be unacceptable for operational weather surveillance.

Performance can be improved greatly through the incorporation of pulse-to-pulse frequency agility. If the frequency change is made about equal to the video bandwidth, successive ground clutter returns will be fully decorrelated, and the integrated output level for the ground clutter will be nearly zero after about twenty interpulse periods.

Implementation with circularly polarized received components involves a similar integration time in order that the depolarization ratio of the ground clutter signals be near unity (i.e., zero decibels). At this point the orthogonal component can be subtracted from the main component to yield a measure of the rain reflectivity which will have a small error due to the orthogonally polarized component of the rain backscatter.

It appears that, while the selective suppression of ground clutter is a desirable capability for a meteorological surveillance radar, the use of polarization-diversity techniques for this purpose has serious limitations. Ground clutter suppression by filtering the zero-Doppler component in a coherent single-channel radar is an easier technique to implement, although it presents a problem when a major portion of the meteorological signal is near zero Doppler velocity. The further investigation of both of these techniques, and their simultaneous or complementary use, could be a significant aspect of a research program involving a coherent polarization-diversity meteorological radar.

## VII. NEW TECHNIQUES

### A. COHERENT POLARIZATION-DIVERSITY RADAR

Preliminary investigations have shown that coherent polarization-diversity radar offers considerable promise as a meteorological research tool. Some of the possible capabilities of such a system are natural extensions of the work of the National Research Council of Canada and the Alberta Research Council. Other capabilities are suggested by the work of Warner and Rogers<sup>(14)</sup>. Specific capabilities include unambiguous derivation of the drop size distribution in rain, leading to improved accuracy of rainfall rate measurement and documentation of atmospheric propagation conditions; separation of Doppler velocity components due to drop fall speed and air velocity, contributing to improved measurement and better understanding of atmospheric dynamics parameters; and improved detection of hail in rain. Applications to observations of snow and ice crystals have not yet been investigated.

The advantages of the coherent polarization-diversity system result from the capability of obtaining the auto-correlation functions of the two received signals as well as the cross-correlation function, and hence the two power spectra and the cross-spectrum. The spectral functions may be treated by techniques analogous to those applied to the parameters derived from a non-coherent polarization-diversity radar. Thus the two power spectra,  $S_1(f)$  and  $S_2(f)$ , are analogous to the main and orthogonal channel powers and show the distribution of the two signals with Doppler frequency. The cross-spectrum  $S_{12}(f)$  may be treated analogously to the cross-correlation at zero time lag (derived from a non-coherent radar) by examining the

spectral coherency

$$\text{Coh}_{12}(f) \equiv \frac{|S_{12}(f)|}{[S_1(f) S_2(f)]^{1/2}}$$

and the spectral phase

$$\text{Ph}_{12}(f) \equiv \tan^{-1} \left[ \frac{\text{Im}(S_{12}(f))}{\text{Re}(S_{12}(f))} \right]$$

The spectral coherency is the spectral analog of the correlation magnitude derived from a non-coherent radar, and the spectral phase is the analog of the phase of the correlation.

A critical factor in the interpretation of data from such a radar is the effect of propagation on the polarization state of the received signals. Even at 10 cm wavelength, differential phase shift can be significant and leads to measured values of circular depolarization ratio and correlation magnitude larger than the intrinsic values of these quantities. Theory has not yet developed to the point of describing the effects of differential propagation on the spectral functions. Thus, in the following discussion we address the ideal case in which these effects are absent. Turbulence in the scattering medium has the effect of spreading the velocity characteristics of hydrometeors of a given size and shape, and thus has an adverse effect on the information potential of the data. The magnitude of this effect and its spectral characteristics are important in the interpretation of the data, but these are not known at present. For this reason, the effects of turbulence are discussed only in a qualitative way.

The interpretation of data from a coherent polarization-diversity radar, as presently envisioned, focuses on the power spectra and the

shape information obtained from them. The spectral coherency, defined above, provides a measure of the fraction of oriented scatterers in each spectral band, as an analog of the correlation magnitude obtained from non-coherent radars which is used to deduce the same information for the ensemble of scatterers. With the fraction of oriented scatterers and the empirical size-depolarization relation of McCormick and Hendry<sup>(13)</sup>, the equivalent radius of rain drops may be derived from the ratio of the power spectra in each band. The result is the drop size as a function of measured Doppler velocity. From the known size-fall speed relation one can determine the fall velocity as a function of Doppler velocity and hence the Doppler component due to fall velocity as a function of measured Doppler velocity. The Doppler components due to air velocity and fall speed are thus unambiguously separated. Computations based on Doppler spectra computed by Warner and Rogers<sup>(14)</sup> show that increasing turbulence results in size overestimation at the lower velocity end of the spectrum and size underestimation at the higher velocity end. These results are shown in Table 2 and in Figure 8. It appears that with spectrum standard deviation due to turbulence or wind shear of less than  $0.5 \text{ m sec}^{-1}$  satisfactory results may be obtained. The effect of turbulence on the size estimation results in a derived Doppler component due to fall speed that is too large at the lower velocity end and too small at the higher velocity end, but monotonically increasing with the measured Doppler. Under such conditions a statistical procedure may be necessary to obtain the air velocity. One can perform a best-fit analysis between the derived Doppler component due to fall speed,  $V_{fd}(v)$ , and the zero-turbulence relation,  $V_{fd} = v - V_a$ . Such a procedure should provide a way of separating the fall speed and air velocity even under conditions of moderate turbulence.

Table 2

Parameters derived from computed Doppler spectra for given values of elevation angle  $\phi$  and turbulence parameter  $\Sigma$  (fraction of oriented scatterers  $F=1$ ).

$\phi$ (deg)	$\Sigma$ (m sec <sup>-1</sup> )	$v$ (m sec <sup>-1</sup> )	$S_1/S_2$ (dB)	$r_{eq}$ (mm)	$V_f$ (m sec <sup>-1</sup> )	$V_{fd}$ (m sec <sup>-1</sup> )
30	1.0	1	-34.2	0.81	5.9	2.95
		2	-20.6	0.97	6.6	3.3
		3	-27.7	1.13	7.2	3.6
		4	-25.2	1.30	7.6	3.8
		5	-23.5	1.46	8.0	4.0
		6	-22.0	1.63	8.2	4.1
	0.5	2	-39	0.66	5.0	2.5
		3	-30	0.99	6.7	3.35
		4	-24	1.41	7.9	3.95
		5	-20	1.75	8.5	4.25
60	1.0	5	-39.5	1.00	6.7	5.8
		6	-36.4	1.18	7.3	6.3
		7	-33.7	1.40	7.8	6.8
		8	-31.7	1.61	8.2	7.1

## Definitions:

- $v$  measured Doppler velocity  
 $S_1, S_2$  spectral density functions  
 $r_{eq.}$  equivalent spherical drop radius  
 $V_f$  fall speed (corresponding to  $r_{eq.}$ )  
 $V_{fd}$  Doppler component due to  $V_f$  ( $V_{fd} = V_f \sin \phi$ )

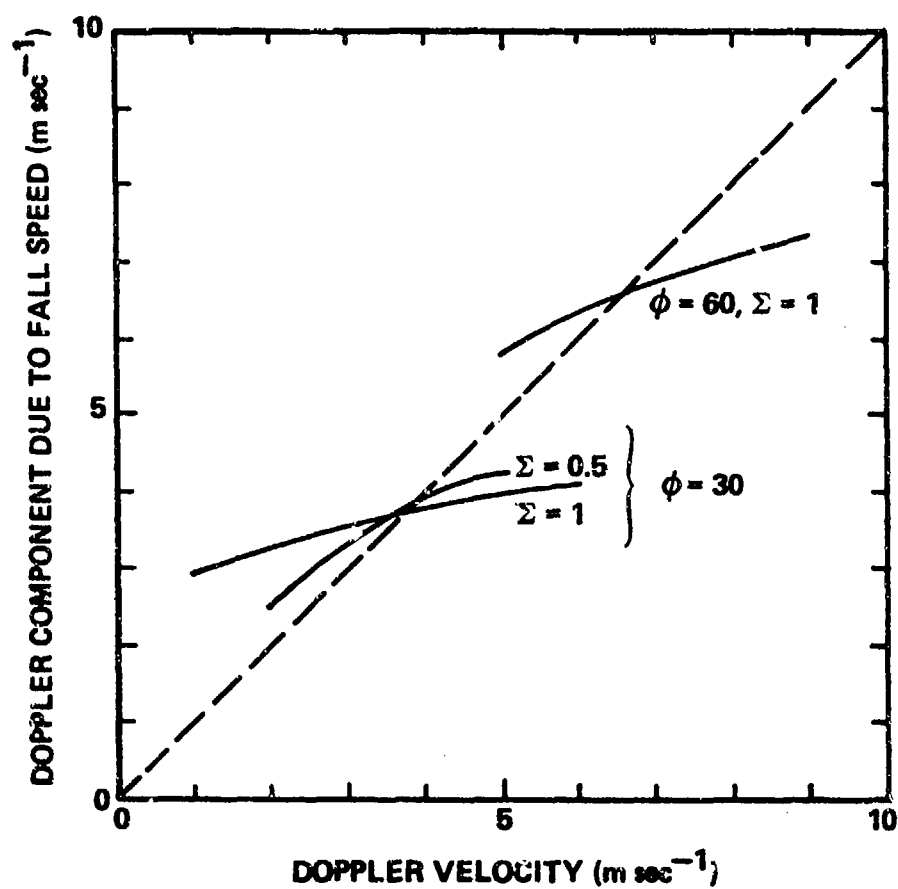


Figure 8. Derived Doppler component due to fall speed as a function of "measured" Doppler velocity for zero air velocity, based on computed spectra of Warner and Rogers (14). Parameter  $\Sigma$  represents spectrum standard deviation due to turbulence or wind shear.

The drop size function derived from the two power spectra and the spectral coherency can be used with the magnitude of the power spectrum of the main channel signal to derive the drop size distribution. It should be noted that the effects of turbulence will be such as to underestimate the number density at the lower velocity end and to overestimate it at the higher velocity end because of the drop sizes. It may be possible to improve the drop size distribution estimate by adjusting the Doppler fall speed components and obtaining better drop size estimates from the adjusted fall speeds.

In principle, the drop size distribution can be obtained and the fall speed separated from the air velocity at any antenna position that provides a measurable Doppler component of fall speed. Thus in an azimuth scan at constant elevation angle, the drop size distribution can be derived for every resolution cell; the vertical air velocity and horizontal convergence are not separable on a single scan, but could probably be obtained from a sequence of scans at different elevation angles. Other dynamical quantities (mean horizontal air velocity and deformation) are derivable as by present single-channel Doppler radar techniques.

The foregoing discussion deals only with observations in stratiform rain. Interpretive possibilities of observations of snow are less certain, because there is no general size-shape function for snow. Thus, the equivalent radius of snowflakes or ice crystals cannot be derived unambiguously from the spectral functions. Further theoretical work may provide guidance in this area, but it seems likely that an empirical approach will be preferable.

The coherent polarization-diversity capability offers some advantages in the detection of hail in severe storms. Present techniques rely on the



reflectivity and circular depolarization ratio, with generally good results, and the inclusion of the correlation magnitude offers hope of even more reliability. Display of the coherent radar data in spectral form offers improvement in that the criteria can be applied in each spectral band. The detection of hail then becomes possible in cases that appear marginal on the basis of the parameters measured by non-coherent radar. At radar elevation angles such as to provide a measurable Doppler component due to fall speed, large hail will appear at the high velocity end of the spectrum with its characteristic values of spectral power ratio and spectral coherency. At low elevation angles hail may be expected to appear in a discrete band of the spectral functions because it is less responsive to variations of the horizontal wind as it falls.

The use of a coherent polarization-diversity radar in hail detection may be illustrated by calculations based on a simple model of mixed rain and hail. The size distribution  $N(D)$ , backscatter cross-section  $\sigma(D)$ , fall speed  $V_f(D)$ , oriented fraction  $\rho_a$ , and power ratio  $v^2$  are modeled as follows:

$$\text{RAIN: } N_R(D) = 8 \times 10^6 \exp(-2.53 D) \quad (R = 10 \text{ mm hr}^{-1})$$

[Marshall and Palmer (38)]

$$\sigma_R(D) = \frac{\pi^5}{\lambda^4} |K|^2 D^6, \quad (|K|^2 = 0.97)$$

$$V_{fR}(D) = 9.43 \{1 - \exp[-(D/1.77)^{1.147}]\}$$

[Best (39)]

$$\rho_{aR}(D) = 1$$

$$v_R^2(D, \rho_a, \phi) = \cos^4 \phi \exp(-10.26 D^{-0.70})$$

[Warner and Rogers (14)]

(38) Marshall, J. S., and Palmer, W. M., 1948: The Distribution of Rain-drops with Size. J. Meteor., 5, 165-166.

(39) Best, A. C., 1950: Empirical Formulae for the Terminal Velocity of Water Drops Falling Through the Atmosphere. Quart. J. Roy. Meteor. Soc., 76, 302-311.

$$\text{HAIL: } N_H(D) = 3.1 \times 10^3 \exp(-0.31D) \quad [\text{Douglas (40)}]$$

$$\sigma_H(D) \text{ after Herman and Battan (41)}$$

$$v_{fH}(D) = 4.11 D^{1/2} \quad [\text{Martner and Battan (42)}]$$

$$\rho_{\alpha H}(D) = 0$$

$$v_H^2(D, \rho_\alpha, \phi) = 0.03 \quad (\text{CDR} = -15\text{dB})$$

where units are  $\text{m}^{-4}$ ,  $\text{m}^2$ , and  $\text{m sec}^{-1}$  but  $D$  is in millimeters in the equations for  $N$ ,  $v_f$ , and  $v^2$ . In the absence of propagation effects and with zero air velocity, the spectral functions are given by

$$S_1(v) dv \propto \sigma_R(D) N_R(D) v_R^2(D) dD_R + \sigma_H(D) N_H(D) v_H^2(D) dD_H$$

$$S_2(v) dv \propto \sigma_R(D) N_R(D) dD_R + \sigma_H(D) N_H(D) dD_H$$

$$S_{12}(v) dv \propto \sigma_R(D) N_R(D) \rho_{\alpha R}(D) v_R(D) e^{j(\delta+2\alpha)} dD_R + \sigma_H(D) N_H(D) \rho_{\alpha H}(D) v_H(D) e^{j(\delta+2\alpha)} dD_H$$

Using the model values for  $\rho_\alpha$  we obtain the coherency

$$\text{Coh}_{12}(v) = \frac{\sigma_R(D) N_R(D) v_R(D) (dD_R/dv)}{\left\{ \left[ \sigma_R N_R v_R^2 \frac{dD_R}{dv} + \sigma_H N_H v_H^2 \frac{dD_H}{dv} \right] \times \left[ \sigma_R N_R \frac{dD_R}{dv} + \sigma_H N_H \frac{dD_H}{dv} \right] \right\}^{1/2}}$$

(40) Douglas, R. H., 1964: Hail Size Distribution. Preprints 11th Wea. Radar Conf., Amer. Meteor. Soc., Boston, 146-149.

(41) Herman, B. M., and Battan, L. J., 1961: Calculations of Mie Back-scattering from Melting Ice Spheres. J. Meteor., 18, 468-478.

(42) Martner, B. E., and Battan, L. J., 1976: Calculations of Doppler Radar Velocity Spectrum Parameters for a Mixture of Rain and Hail. J. Appl. Meteor., 15, 491-498.

The results of the calculations are shown in Figure 9 for  $\lambda = 0.1$  m and  $\phi = 30^\circ$ . The inflections in the spectra are due to the cut-off of the rain component at a Doppler velocity of  $4.7 \text{ m sec}^{-1}$  and the fact that the scatter due to hail does not exceed the scatter from rain at and below this velocity. With suitably chosen model distributions one could obtain spectra that did not have the inflection. The coherency illustrates the effect of the increasing fraction of hail with hydrometeor size and fall speed. At low velocities the coherency is near unity, indicating that all the scatter in these bands is due to rain. Above about  $2 \text{ m sec}^{-1}$  the scattering due to hail increases, and the coherency decreases to the point that the scattering is entirely due to hail, about  $5 \text{ m sec}^{-1}$ .

If all the hail had fall speed less than  $9.4 \text{ m sec}^{-1}$ , it could be distinguished from rain on the basis of the coherency. The coherency obtained from observations of rain would have a uniformly high value, whereas the presence of hail would result in a local decrease. Such a feature would provide not only an indicator of the presence of hail but also a measure of its size, according to its location on the velocity scale.

The role of propagation effects will require further investigation, as noted above, but offers some interesting and beneficial possibilities. Since propagation effects are independent of target velocity, they should affect all spectral bands equally. Spectral bands carrying greater returned power will be less affected than others, and if spectral characteristics due to scattering can be approximated or derived independently then the propagation term can be separated. This offers a more precise determination of the propagation quantities than is derivable from non-coherent polarization-diversity radars and suggests that parameters of the scattering medium may be derivable even in the presence of propagation effects. If the

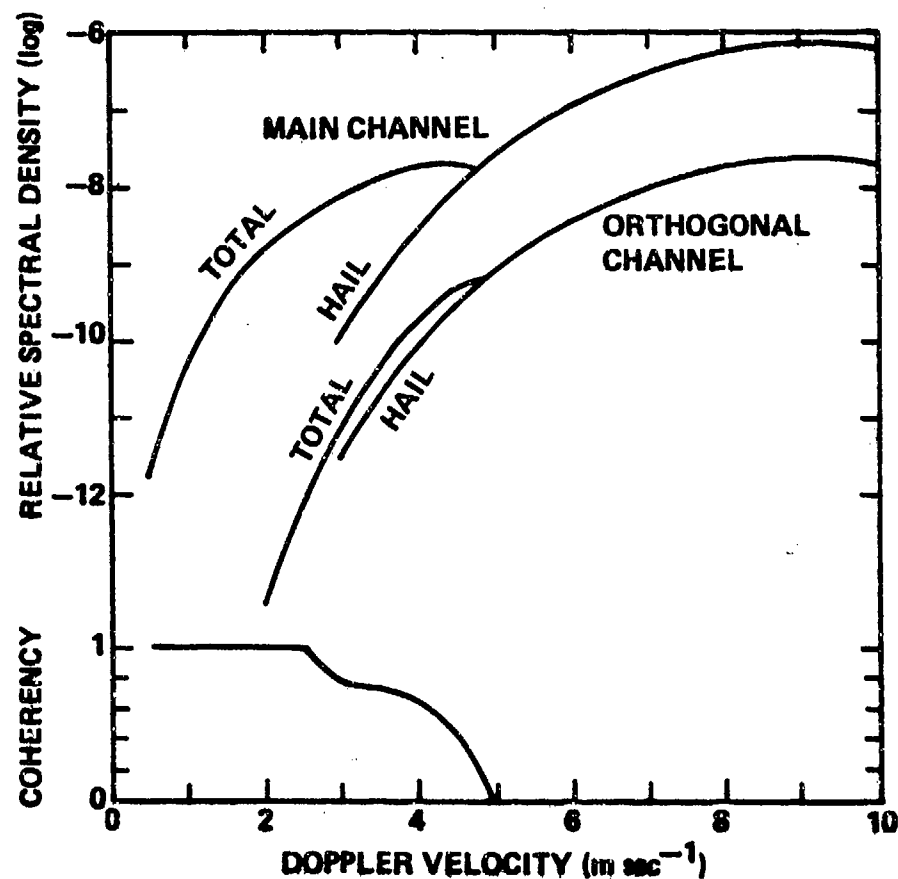


Figure 9. Spectra and coherency computed from rain and hail model described in the text. Signal in both channels below about  $2 \text{ m sec}^{-1}$  is dominated by rain, as indicated both by the relative magnitudes of the spectra and by the coherency near unity. Above  $2 \text{ m sec}^{-1}$  the signal component due to hail increases, with a resulting decrease in coherency to the point that the signals are due entirely to hail, above  $5 \text{ m sec}^{-1}$ .

propagation medium undergoes changes due to varying electric fields as deduced by Hendry and McCormick,<sup>(18)</sup> then the separation of propagation effects should be somewhat easier and numerically more certain.

The combination of coherence and polarization-diversity offers significant advantages over the separate use of these capabilities. For observations in rain the advantages are based on the size-shape relation of rain drops, and it appears possible to derive the drop size distribution and to unambiguously separate the Doppler components due to fall speed and air velocity. Other advantages also arise from the spectral display of the radar data. These include more reliable detection of hail and, in some cases, the separation of propagation effects and scattering effects in the spectral functions.

#### B. POLARIZATION-DIVERSITY LIDAR

One of the present limitations on the use of lidar as an atmospheric probe is the difficulty of deriving the reflectivity or scattering cross-section of hydrometeors from the backscattered signal. This is due to the difficulties of measuring the output energy of each pulse precisely and of determining the atmospheric propagation parameters for each pulse. Pulse rates of  $0.1-0.5 \text{ sec}^{-1}$  and beam widths of  $1-2 \text{ mrad}$  typically used for lidar atmospheric measurement preclude the interrogation of a given array of hydrometeors more than once. While there is no need for time integration of signals at optical wavelengths (because the scatterers are typically much larger than the wavelength), the sampling rate restriction places more strict requirements on the accuracy of quantitative signal measurement, since transmitted power variations and propagation variations cannot be averaged without sacrificing accuracy in measuring scattering parameters.

The problem of reflectivity measurement is being studied by V. E. Derr (private communication) and others, and it seems likely that it will be solved within the next few years.

If the capability of absolute reflectivity measurement is available in addition to the measurement of depolarization ratio, then the discrimination of high-altitude aerosol layers from clouds will become possible in nearly all situations. The lidar discrimination between high-altitude aerosols (such as might result from rocket or jet exhausts) and ice phase hydrometeors at around 12 km altitude can be readily achieved on the basis of linear depolarization ratio from ground base observations, given a sufficiently narrow beam width (about 1 mrad) receiver. The LDR's characterizing the hydrometeors will be approximately 0.5-0.8 whereas the aerosol LDR's resulting from multiple scattering will be no more than about 0.05-0.1 depending on their number density. The discrimination would be aided in many cases by the fact that aerosol layers have lower reflectivity than clouds. Large or dense aerosols could have reflectivity comparable to that of clouds, about  $10^{-2}$  to  $10^{-3}$  sterad $^{-1}$ , according to Derr. In such cases the LDR provides the discriminant between aerosols and ice crystal clouds, and the remaining ambiguity is between aerosols and liquid water clouds.

It appears that the use of multiple wavelength lidar observations would be necessary in order to resolve the ambiguity by remote measurement. Differential scattering characteristics due to the wavelength-dependence of the refractive index of the scattering hydrometeors could then be measured. The use of multiple wavelength lidar for atmospheric observations is thus the most general means of discriminating among aerosols and liquid and solid hydrometeors.

## VIII. CONCLUSIONS AND RECOMMENDATIONS

The history of research in meteorological applications of polarization-diversity radar and lidar, reviewed by Metcalf et al,<sup>(1)</sup> reveals that much of the work that has been done has been of a piecemeal nature with typically limited objectives. Thus, there have been several instances of inconclusive or severely limited results due to equipment inadequacies, and a few cases of outright duplication of results by researchers working independently. Despite this lack of continuity, substantial progress was made throughout the 1950's and 1960's in the theory and measurement of scattering and propagation parameters and in the design of radar equipment. Notable exceptions to the foregoing assessment have been the research programs of the National Research Council of Canada and the Alberta Hail Project, under the Alberta Research Council. These organizations proceeded systematically in the late 1960's to design radar equipment capable of precise measurement of polarization parameters and to develop the theory of interpreting the data they recorded. It is a consequence of these programs that the joint use of CDR and reflectivity for hail detection has been documented, the actual and potential role of the percent correlation in identifying hydrometeor thermodynamic phase has been identified, orientation angles of hydrometeors have been measured, and differential propagation parameters have been obtained from backscatter measurements. In the past few years researchers at Ohio State University have proposed and implemented the use of differential reflectivity for measuring rainfall rate and have suggested its use for identifying hail. They have also used the T-matrix, or extended boundary condition, formulation for scattering from arbitrarily shaped dielectrics to compute differential scattering parameters for hail.

Backscatter measurements by polarization-diversity lidar have been made in laboratory and field experiments and have shown the capability of lidar for effectively discriminating solid and liquid hydrometeors in clouds. In a sense, polarization-diversity lidar techniques now are at a stage similar to that of polarization-diversity radar in the early 1960's. However, given the rapid development of laser technology at present and the development of polarization-diversity radar meteorology that has occurred in the 1960's and 1970's, it may be expected that both the measurement capabilities and the interpretive theory and practice of polarization-diversity lidar meteorology will undergo rapid development in the next few years.

At the present state of polarization-diversity radar and lidar techniques, clouds and precipitation comprising all solid or all liquid hydrometeors can be unambiguously identified in nearly all cases. Mixtures of solid and liquid hydrometeors are more difficult to define, although the presence of ice, e.g., hail, can be determined fairly reliably. Polarization diversity techniques also provide the means of measuring the average reflectivity-weighted shape of the scattering ensemble, which can be related to size in some cases. Average shape can also be determined from differential reflectivity measurement at orthogonal linear polarizations; this procedure yields a more accurate measure due to less effect of differential propagation in moderate to heavy rain.

The derivation of propagation parameters from backscatter measurements has been done only at 1.8 cm. Results of this research indicate a variety of potential benefits including increased penetration of precipitation by electromagnetic signals and improved suppression of meteorological "clutter". Other applications of polarization-diversity including the coding of Doppler radar pulses for circumventing the range-velocity ambiguity and the selective



suppression of ground clutter in meteorological radar displays, offer certain operational advantages but for various reasons appear to be worthy of further research only as subsidiary objectives of a larger research program.

A significant area with many potential applications and benefits which has received almost no attention heretofore is the use of coherent polarization-diversity radar. Possible capabilities of such a radar include measurement of the drop size distribution in rain, unambiguous separation of Doppler components due to fall speed and to air velocity, improved detection of hail in rain, and separation of propagation effects from scattering effects. Interpretation of backscatter data from snow or ice crystals is not understood at the present time, but warrants further study. These capabilities offer benefits in detection of severe storm hazards, improved input to numerical models of storm dynamics, better understanding of the characteristics of the atmosphere as a propagation medium, and determination of scattering parameters of ice-phase hydrometeors.

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